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Increasing the sustainability of household cooking in developing countries: Policy implications

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Although 40% of the global population relies on traditional biomass use, mainly firewood and charcoal, for cooking, traditional biomass has received very little attention in the current biomass debate, because of its considered primitive and unsustainable nature. In this review, we discuss how the sustainability of household cooking in developing countries can be improved.

Indoor air pollution due to incomplete combustion of traditional biomass causes the death of 1.45 million people every year, mainly of women and children, who also carry the heavy burden of fuelwood collection. In addition, charcoal production and combustion is responsible for very high greenhouse gas emissions per unit of energy. On the other hand, fuelwood production and trade is of vital importance for local economies and serves as safety net for the poorest people. Moreover, fuelwood collection is not a driver of deforestation and global fuelwood shortage will not occur, despite local problems of fuelwood provision.

There are two distinct policy alternatives to increase the sustainability of cooking in developing countries. The first option is to climb the energy ladder and to switch from solid fuels to fossil fuels (LPG or kerosene), biogas or electricity. As this largely avoids the severe health damages of traditional biomass use, this option is considered the most desirable by numerous countries and by international organizations. However, as most developing countries are far away from meeting the necessary requirements, related to infrastructure, economics and local culture, expecting a large-scale switch to liquid fuels or electricity is unrealistic.

In that case, the second policy option, increasing the sustainability of the current traditional biomass system, must be considered. This can be realized by an integrated approach, in which national and regional fuelwood policies are adapted, improved systems for charcoal production are implied and improved stoves, in combination with chimneys, are distributed.

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1. Introduction

In 2007, 1031 Mtoe (Million tons of oil equivalent) or 12.9% of the total energy consumption was derived from biomass [1], comparable to the amount of energy consumption from electricity or gas [2]. In contrast to public perception, only 3% of the biomass consumption came from liquid biofuels in the transport sector. Traditional biomass use for cooking and heating accounted for 74% of the total biomass energy consumption and was more than 22 times as important as liquid biofuels.[1] Most scenarios say that at least until 2030, traditional biomass use will remain more important in terms of energy consumption than "modern" biomass use in the industrial and transport sectors [4].

Nevertheless, traditional biomass use has received remarkably little attention in the current biofuel debate, for it is considered unsustainable and primitive [5]. This attitude ignores the reality that traditional biomass use is and will remain extremely important for the global energy management and in particular for the poorest people. Hence, increasing the sustainability of traditional biomass use could have a tremendous effect on the sustainability of the global energy consumption.

In this paper, we will focus on policy interventions to increase the sustainability of wood-based traditional biomass use, with an emphasis on wood, the dominant fuel for traditional biomass use, in developing countries.

2. Historical overview: fuelwood crisis, re-appraisal and current policies

2.1. 1970s – Mid 1980s: fuelwood crisis

It wasn't until the mid-1970s that the total amount of fuelwood consumed for traditional biomass in developing countries was estimated. This lead to a first appraisal of the important socio-economic role of traditional biomass use [6]. In addition, future projections of fuelwood consumption were made, though based on inelastic models incorporating future population and assuming constant future fuelwood demand per person [5,7]. These projections showed that future fuelwood requirements were much larger than the annual regrowth in forests, which fuelled the widely accepted idea that fuelwood collection was a major cause of deforestation [8]. It was projected that by 2000, 2.4 billion people would suffer from a lack of fuelwood [9]. As this "fuelwood gap" was expected to cause an "other energy crisis" [6] with large socio-economic consequences for the poorest people, the international community responded with large development programs. These programs consisted of a large number of incentives to bridge the fuelwood gap, either by increasing the fuelwood production or by increasing the efficiency of fuelwood conversion. This last aspect was obtained by introducing improved cooking stoves and improved charcoal kilns and by replacing solid fuels with liquid fuels such as LPG and kerosene [10]. The emphasis of the programs was on fuelwood provision, which was mainly done by establishing government-controlled woodlots [8].

2.2. A reappraisal of the fuelwood crisis

Although based on good intentions, it became clear in the mid-1980s that the large majority of the development programs had failed. Even in urban regions, people did not switch massively to improved stoves or to liquid fuels [8]. Yet, the expected fuelwood gap was not observed [3,11–13]. It became clear that fuelwood is not a major driver of deforestation, partly because fuelwood is collected mostly outside forests. This gradually led to a better understanding of the fuelwood issue and to a reappraisal of the fuelwood crisis.

Due to huge shifts in international politics, in combination with the absence of the fuelwood gap and the limited success of the fuelwood programs, the attention of the international community for traditional biomass use gradually imploded [14]. In the 1990s and 2000s, the number of development programs was cut

[1] Traditional biomass use was estimated as 765 Mtoe, based on the available number of 2002 [2] and taking the common assuming that this has remained roughly the same in the years afterwards [3].

back. Fuelwood supply was of limited consideration in most rural development programs started in the nineties [10]; instead, these programs focused on the replacement of solid fuels by liquid fuels and electricity, inspired by new insights in the large health consequences associated with fuelwood burning [5,10,15].

2.3. Current policies

Nowadays, switching to fossil fuels or electricity remains the dominant view on the traditional biomass issue, alongwith improved cook stove programs [e.g. 4,16]. Although energy was not one of the eight millennium goals of the United Nations Millennium Project, traditional biomass use and energy poverty are strongly linked with all of the goals [16] and the United Nations Millennium Project formulated the following ambitious "need for a quantum leap" as part of the Millennium Goals [16]: "*By 2015, [the goal is] to reduce the number of people without effective access to modern cooking fuels by 50%, and make improved cooking stoves widely available*".

Next to the view that traditional biomass use should be replaced by liquid fuels or electricity, the fuelwood crisis narrative – and its associated negative vision on fuelwood extraction – is still widely established in international organizations, governments and NGOs, despite the lack of empirical evidence [5,10,14,17]. This is often translated in a ban on fuelwood extraction from forests.

It is becoming increasingly clear that this current policy has its limitations. With 1 billion people short of using improved stoves and at least 325 million short of getting access to electricity [4], the quantum leap aspired by the United Nations Millennium Project currently rather looks like a small hop. Several scientists have argued that, in denying the reality of a large population depending on fuelwood for cooking, the current mixed policies of the fuelwood crisis narrative and the replacement with liquid fuels or electricity are even counterproductive and hamper a sustainable use of fuelwood resources [5,14,18]. Hence, there is a call for a new appraisal of fuelwood for traditional biomass use and for an increased interest for this issue in national and international policy.

3. Aspects related to fuelwood for traditional biomass use

3.1. Importance for people and for local economy

3.1.1. Number of people relying on fuelwood

In 2004, 560 million households in developing countries relied on traditional biomass (fuelwood, charcoal or dung) for cooking. This corresponds with a total of 2.68 billion people, 40% of the global population [4]. More than half of these people live in India, China and Indonesia; yet the highest proportion of people relying on traditional biomass is found in Sub Saharan Africa (SSA) [12] (Table 1). In SSA, 94% of the rural households and 41% of the urban households use wood or crop residues as their primary source of household energy, whereas 4% of the rural and 34% of the urban households rely on charcoal [19] (Table 1).

Table 1
People relying on biomass resources as their primary fuel for cooking in 2004. After IEA [12].

	Total population		Rural		Urban	
	%	Million people	%	Million people	%	Million people
Sub-Saharan Africa	76	575	93	413	58	162
North Africa	3	4	6	4	0.2	0.2
India	69	740	87	663	25	77
China	37	480	55	428	10	52
Indonesia	72	156	95	110	45	46
Rest of Asia	65	489	93	455	35	92
Brazil	13	23	53	16	5	8
Rest of Latin America	23	60	62	59	9	25
Total	52	2528	83	2147	23	461

According to the latest projections by IEA [4], 2.8 billion people will still rely on traditional biomass use for cooking in 2030, 82% of which live in rural areas. The total number of people relying on traditional biomass is projected to decrease in China and India, but to increase in the rest of developing Asia and in Africa [4,20].

3.1.2. Fuelwood consumption

The high dependence on traditional biomass for energy is reflected by the fact that 80% of the wood harvested in developing countries (90% of the wood harvested in Africa) is used for fuelwood [3,21,22]. However, estimations of total fuelwood consumption vary considerably between studies. The FAO estimate of annual global fuelwood production, 1.85 Gm^3, is much lower than previous estimations of 2.9 [24] or 3.8 Gm^3 [23,25]. Global annual firewood consumption is believed to have peaked in 1990s at 1.6 Gm^3 and to have declined slowly ever since; in contrast, fuelwood consumption for charcoal production is increasing rapidly [4,10,26]. Fuelwood projections indicate that the consumption of charcoal will double between 2000 and 2030, whereas the consumption of firewood will increase with 24% [10], in line with the expected increasing number of households reliant on fuelwood for cooking [4].

There are two main reasons for the large variation in fuelwood consumption estimates. First, fuelwood is consumed outside the market systems and does not enter official wood trade statistics. Second, a large part of fuelwood originates from non-forest trees. In developing countries in Asia, it is estimated that 67% of the fuelwood supply comes from non-forest trees [27,28]. The share of non-forest wood for total traditional fuelwood use increases with decreasing forest cover. In the Sahel region, for instance, 90% of the fuelwood comes from trees outside forests [29]; in the rest of SSA, non-forest trees make up half of the traditional fuelwood consumption [30]. Estimates of non-forest wood consumption are much more difficult to assess than those of forest wood and therefore vary greatly, from 0.55 [23] to 1.1 Gm^3 [30] per year.

3.1.3. Importance of firewood and charcoal for local economies

There are no data available of the global revenue or employment generated by firewood or charcoal production or trade; however, regional and national studies suggest their importance for the economy of developing countries [3,5,10,11]. In the developing countries of Asia, including China and India, fuelwood is the main source of income for 10% of the rural households [31]. In India alone, three to four million people are employed in the fuelwood sector [32]. From the review studies of Bhattarai [31] and Arnold et al. [8], it is clear that fuelwood production is a very important source of revenue for rural people in virtually every developing country.

Through the accessibility of the resource and the ease of entrance into the market, firewood trade is accessible for everybody and provides a critical earning activity for marginalized urban and rural residents [10,12,33]. For many rural households, firewood trade helps to bridge the seasonal income gaps and serves as a safety net activity in years of low agricultural production [8,14,34]. For women, it can be an important source of income to meet household expenses [8]. Some scientists even consider fuelwood trade as an important engine of economic growth [5,13,35]. Nevertheless, due to the very low barrier to enter the market, competition is often very hard and the prices remain low, severely limiting economic investments in fuelwood production or trade.

The story is different in the case of charcoal. Charcoal trade is mainly concentrated around urban areas and is often well-organized and controlled by merchants [8,10]. The trading

networks result from livelihood specialization rather than from resource scarcity [5,11].

As a free or as the cheapest available energy source, fuelwood is also of obvious economic importance for the consumers. Increasing fuelwood prices or decreasing fuelwood availability causes families to (partially) switch to other energy sources or to increase the efficiency of the fuelwood use. Poor households respond by shifting to dung and agricultural waste, increasing the time for firewood collection and/or decreasing the cooking, with all due consequences [10].

3.2. Sustainability of fuelwood production

3.2.1. Fuelwood production and supply

As mentioned in Section 2.1, the international community was expecting a fuelwood gap by the end of the 1990s; however, no severe fuelwood shortages have been reported, despite the limited success of most development programs. There are two main reasons for this.

First, the fuelwood gap calculations were based on the sustainable regrowth of the forest area. However, as mentioned, the largest part of firewood (but not fuelwood for charcoal) originates from non-forest resources [5,11,12]. Moreover, the future fuelwood demand was overestimated, because the flexibility of the people to adjust to changing fuelwood availability was underestimated [8].

Second, the major rationale behind the fuelwood gap narratives was the assumption that fuelwood extraction is a major driver of deforestation. However, overwhelming evidence shows that deforestation is caused by other factors. Particularly in urban areas, deforestation can be ascribed to extension of the agricultural area or to residential development, two more profitable land uses for the land owners or local communities than forests [5,10,14,36].

Most tropical forest species, particularly those of Miombo woodlands and other semiarid forests, are well adapted to frequent disturbances and regrow vigorously after coppicing [e.g. 37,38–40]. In addition, cutting activities often resemble sustainable harvesting rather than the often presumed pillaging with rapacious extraction techniques [5]. Collectors of firewood prefer dry wood – dead or dying trees – rather than living trees, and commercial fuelwood suppliers, harvesting wood for charcoal production, prefer to leave smaller size classes untouched, because of their low economic value [13]. In regions with high fuel prices, low forest cover and low non-forest wood availability, fuelwood demand can even be a driver of afforestation, as was for instance observed in the Cebu region of the Philippines [17], in good agreement with the theory of forest transition [41–43].

There is now a broad consensus among scientists that a global fuelwood crisis will not occur and that future stocks will satisfy the increased demands. Still, it must be recognized that local fuelwood shortages occur, as was for instance reported in regions in India [44], Tanzania [45] and in Southern Africa [46].

There is particular concern on the sustainability of charcoal extraction [47]. Despite the fact that charcoal stoves are more efficient than firewood stoves, much more fuelwood is required for charcoal than for firewood use [14,48,49]. However, as for firewood and in contrast with common belief, charcoal extraction as such is not a driver of deforestation [e.g. 50–52]. Still, charcoal extraction can be a first step of forest degradation, when it is followed by intensive grazing [51] or by conversion into agricultural fields [53] or when charcoal extraction is too frequent. As disturbance is more regular in the vicinity of roads around major cities, charcoal extraction can be problematic in these regions [8,54] and can therefore pose an indirect threat to the persistence of forests, for example in Tanzania [48]. Moreover, long-burning charcoal is preferred for cooking, requiring high-density wood, typical of native slow-growing species, which need longer periods to recover [48,53,55,56]. In these forests, charcoal extraction in native forests can cause losses in biodiversity [57–59] and can lead to small declines in total forest carbon levels [53].

3.2.2. Fuelwood conversion

The amount of energy that can be generated from fuelwood is expressed by the heating value. The higher heating value (HHV) is the amount of heat released by one kg of wood when all reaction products (including the water) have returned to a temperature of 25 °C. The HHV of dry wood (HHV_{dry}) varies less than 15% between species and is on average 20–22 MJ kg^{-1} for softwoods and 19–21 MJ kg^{-1} for hardwoods [60,61]. Softwoods have higher values of HHV because of their higher lignin content [61]. As such, the actual higher heating value (HHV_{act}) or gross heating value (GHV) of wood is much more influenced by its moisture content than by the tree species-specific wood structure. It can be calculated from the moisture content (MC; [%]) as $GHV = HHV_{act} = HHV_{dry}\,(1 - MC/100)$. The moisture content of living wood is normally between 30 and 55% [60]; hence, when wood is not dried before it is burned, 30–55% of the energy in the wood is needed to evaporate the remaining water and gets inevitably lost. The water content of air-dried wood is between 12 and 20% and has a GHV of 13–16 MJ kg^{-1}.

The thermal efficiency of a stove is quantified in water boiling tests and is defined as the ratio of energy entering the pot to the HHV_{dry} [62]. The thermal efficiency of firewood burned in open fires is about 5%, the efficiency of traditional wood stoves is typically about 10% and that of improved stoves is between 13 and 40% [62].

Charcoal is created by heating wood in the absence of oxygen so that combustion is prevented. Heating releases the wood's volatile compounds, resulting in a lightweight burning fuel. Charcoal has a higher heating value of about 28 MJ kg^{-1}, depending on the total carbon content [60]. The theoretically achievable conversion efficiency (kg of charcoal per kg of dry wood) of charcoal from woody biomass is in the range of 50–80% [63]. However, the pit or earth-mound kilns, traditionally used in most developing countries, including in SSA [20], for charcoal production for household use [64,65], reach conversion efficiencies of 10–15% [18,63,66]. The most efficient non-industrial system available in developing countries has a conversion efficiency of 35% (See Section 4.2.1). The thermal efficiencies of charcoal-burning stoves used for cooking in developing countries range from 12 to 27% [62], although efficiencies up to 46% have been recorded in improved stoves [67].

3.3. Health problems related to traditional biomass use

3.3.1. Toxicity of fuelwood combustion

Traditional stoves are not only characterized by very low energy conversion efficiencies, they also emit a large amount of toxic elements. The most important toxic emissions are suspended particles, carbon monoxide, nitrogen oxides, methane, formaldehydes and other organic compounds (mostly grouped into the Non-Methane Organic Compounds or TNMOC) [3]. Carbon monoxide, methane and TNMOC are products of incomplete combustion (PIC). The PIC content of firewood carbon can be very high. Smith et al. [68] tested several types of biomass stoves. No biomass stoves diverted less than 5% of the fuel carbon into PICs, whereas several diverted more than 20% into PICs. Similar results were obtained in other studies [e.g. 62,69]. In combination with the low conversion efficiencies, total CO_2 and PIC emissions per unit of delivered energy are very high for most types of firewood [68].

Emissions from charcoal stoves are lower than those of firewood stoves [20,67,68]. However, during the cold start, charcoal stoves produce a large amount of smoke, which can annul the emission reduction. Charcoal stoves are typically started outside and are only brought indoors after the charcoal is hot, when little smoke is produced and emissions of pollutants can be up to 90% lower than those

of firewood [20,69]. However, charcoal stoves emit larger amounts of carbon monoxide (CO) than fuelwood stoves [20,68,70].

3.3.2. Health problems

Indoor air pollution from solid fuels is the cause of very severe health problems. There is overwhelming evidence that indoor air pollution is a major cause of acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD) and lung cancer [3,71–73]. There is also moderate evidence that air pollution from indoor cooking causes cataracts, tuberculosis, asthma attacks and lower birth weight [72,74]. In addition, indoor air pollution also causes indirect health effects, as it aggravates the suffering and shortens the life of people suffering from malaria, TBC, HIV/AIDS or chronic cardiovascular or respiratory diseases [12].

ALRIs comprise a set of clinical symptoms caused by viruses or bacteria and include pneumonia, bronchitis and bronchiolitis [75]. ALRIs are one of the world's leading killers of young children. In developing countries, children under 5 suffer 0.29 ALRI episodes per child per year [75]; children exposed to indoor air pollution are 2–3.3 times more likely to suffer from serious ALRI than unexposed children [72]. In Sub-Saharan Africa, 690,000 children die each year of the consequences of ALRIs; an estimated 51% or 350,000 deaths are directly attributed to indoor air pollution caused by traditional biomass smoke [20]. Without a systematic change in fuel-use patterns, 8.1 million children will die from ALRIs between 2000 and 2030 in Sub-Saharan Africa [20]. In addition, overnight carbon monoxide poisoning due to charcoal burning causes annually thousands of deaths worldwide [70]. In all developing countries, indoor smoke from solid fuels takes 1.45 million lives each year (400,000 in Africa) [16]; with the current policies, this number is expected to increase up to 1.50 million lives by 2030 [4]. As such, indoor air pollution associated with biomass use is one of the largest health threats of our planet, only beaten by malnutrition, unprotected sex and lack of clear water. It is responsible for more direct deaths than malaria [16].

3.4. Greenhouse gas emissions

At first sight, one might assume that, as long as the wood is harvested in a renewable way, the use of fuelwood for traditional biomass does not cause net greenhouse gas emissions and is essentially a sustainable energy system. However, as mentioned in Section 3.2, domestic biomass-burning stoves are characterized by low combustion efficiency and the formation of PICs. These include substances as CO, CH_4 and non-methane hydrocarbons (NMHCs), which have a higher global warming potential (GWP) than CO_2. As such, the amount of greenhouse gases emitted is not only a function of the renewability of the wood harvest, but also of the stove type, kind of wood and, in case of charcoal, of the charcoal production process.

The calculation of the total climate change impact of traditional biomass fuels is complicated by uncertainties regarding the GWP concept itself. The global warming potential of a constituent was defined by IPCC as "*the time-integrated radiative forcing due to a pulse emission of a given gas, relative to a pulse emission of an equal mass of CO_2*" [77]. In other words, GWP expresses how much smaller or larger the greenhouse contribution of a constituent is in comparison with CO_2 for a specific time horizon. GWP estimates of some atmospheric constituents, including CO and NMHCs (non-methane hydrocarbon) have a very large uncertainty. In addition, the time horizon very much influences the GWP. CO_2 is a stable element; as such, constituents with a limited lifetime will have a larger GWP for shorter time horizons. This is the case for all PICs related to traditional biomass use [68,78]. The choice of time horizon is often made rather randomly, for there is no universal "best" time horizon [77]. The IPCC used an arbitrary time horizon of 100 years, which was also used in the Kyoto protocol. In traditional biomass studies, however, a time horizon of 20 years is usually taken [but not by 53], following a pioneer study of Smith et al. [68] (Table 2); however, given its importance for the results, this choice was hardly elucidated.

Table 2
The global warming commitment (GWC), expressed as the grams of C as CO_2 equivalents per MJ of delivered energy, for a LPG-stove, a kerosene press stove and for the least and most GHG-intensive stove–fuelwood combination tested.

	Eucal-Imet[a]	Acacia-ivc[b]	LPG	Kerosene press
Time horizon: 20 years				
Non-renewable	555	930	139	176
Fully renewable	181	481		
Time horizon: 100 years				
Non-renewable	443	605	132	158
Fully renewable	69	156		

Data were derived from Smith et al. [68].
GWC was calculated using Eq. (2) in Smith et al. [68]. The GWP of CO_2 was 1 for both horizons; that of CO was 4.5 (20 years) and 1.9 (100 years) [76]; of CH_4: 72 and 25 [76]; of NMHC 12 and 4.1 [68]; of N_2O 290 and 300 [68]; all GWPs are on a mole basis (for NMHC, a mole weight of 18 was assumed). The fully renewable GWC were calculated by assuming that all carbon (CO_2 ánd non-CO_2) emitted were taken up again.
[a] Eucalyptus wood burned in an improved metal stove, the combination with the lowest GWC (20 years horizon) in the study of Smith et al. [68].
[b] Acacia wood burned in a improved vented ceramic stove, the combination with the highest GWC (20 years horizon) in the study of Smith et al. [68].

The total climate change impact of a fuel is given by its global warming commitment (GWC; the total amount of greenhouse gas contribution), the sum of the products of the GWP of each constituent with the amount emitted. If alternative measures are used instead of GWC, such as the global warming change potential (GTP) [79], the relative weight of the PIC constituents – hence, the total GTP – is much lower [77]. A further complication of the GWC-estimation is the limited number of studies comparing the GWC of the different energy systems.

However, some trends are clear:

- The GWC of charcoal is much higher than that of firewood. First, charcoal production with traditional pit or earth mound kilns releases 1800 g of CO_2 equivalent units per MJ [80], taken a time horizon of 20 years. Second, assuming renewable harvest, the GWC of charcoal burning is about 800 g C of CO_2-equivalent units per MJ for a 20 year time, due to the high level of CO and CH_4 emitted [78]. This makes a total of about 2600 g of CO_2 equivalent units per MJ of emitted energy. In contrast, firewood burning has a GWC of 200–400 g C.
- Improved stoves do not always emit less GHG than traditional stoves, and stoves with chimneys emit more GHG than stoves without chimneys [68,78].
- Do fossil fuel stoves emit less or more GHG than traditional biomass stoves? In a study comparing several stove and fuel types in India, the use of LPG and kerosene had lower GHG contributions than firewood or charcoal, even when the fuelwood harvest was renewable and when improved stoves were used [68]. The reason for this is that fossil fuel stoves (LPG and kerosene) are much more efficient in combustion and in heat transfer than solid biomass stoves [68,78]. These counterintuitive results were picked up by scientists and were an important argument in international policy in favor of replacing traditional biomass by fuels [e.g. 16]. However, a re-analysis of the data shows the important role of the time horizon. This is illustrated in Table 2. If harvesting is unsustainable, the use of LPG or kerosene has the lowest GWC, regardless the time horizon. On the other hand, if a time horizon of 100 years is considered and if the harvest is fully sustainable (as is most often the case for firewood, see Section 3.2.1.), the

GWC of the most efficient fuel-stove combination tested (*Eucalyptus* wood in an improved metal stove) is only 52% of the LPG stoves and 43% of the kerosene pressure stoves; the GWC of the most GHG-intensive stove (*Acacia* wood burned in an improved vented ceramic stove) is still (slightly) lower than the GWC of the kerosene press stoves.

In the study of Smith et al. [68], only the GHG-effect of the fossil fuel burning was considered; the GHG costs of fossil fuel production (land use change, refining) and of transport were ignored. On the other hand, combustion of fossil fuels tends to be much more controllable than combustion of traditional biomass; once cooking is finished, fossil fuel stoves are turned out and combustion stops. This is often not the case for combustion of solid fuels [68]. Because this aspect was not taken into account in the measurements, the difference between the fossil and traditional biomass stoves might actually be underestimated. Although the study was only based on Indian stove types, measurements with other stove types gave comparable GWCs for traditional biomass fuels [e.g. 78].

In conclusion, with the current knowledge, it is impossible to say whether fossil fuels have a higher or a lower GWC than firewood burning. Given the large difference in GWC between charcoal and firewood, it can be concluded that the GWC of charcoal produced in traditional kilns is higher than that of fossil fuels.

3.5. Problems of traditional biomass uses are gender- and child-related

In the largest part of the world, women are traditionally responsible for cooking [4,12,16]. Consequently, women are much more exposed to indoor air pollution than men. According to WHO [16], 511,000 women die from chronic obstructive pulmonary disease due to indoor smoke every year, whereas 'only' 173,000 men die from this disease. As mentioned, children are particularly vulnerable to indoor air pollution and young children, carried on their mother's back, are also exposed to very high levels of indoor air pollution [81].

Wood collection is predominantly a task for women and children, especially girls [4,82,83]. If fuelwood becomes scarcer, the collection time, distance walked and frequency of collection increases [83]. In addition, children have to become more involved in collecting wood [83]. This time-consuming and exhausting task has a high opportunity cost. With increasing fuelwood shortages or increasing distances to fuelwood stocks, children are withdrawn from school in order to collect firewood, reducing their literacy and restricting their economic opportunities [12,82].

3.6. Land tenure conflicts

In many developing countries, forests and other lands are state-owned, but are in practice used by local communities for fuelwood extraction. Bush lands, in whatever state of succession, play a crucial role for providing fuelwood to the local community, particularly to subsistence users who do not own private lands and therefore have only limited access to non-forest tree sources. The importance of these lands for fuelwood provision is often ignored and these lands are often considered "wastelands" by the government [10,84].

Land tenure conflicts were recently reported after phenomena of land grabbing by foreign companies and governments for food and biofuel production [85,86] and will become more important when energy plantations will be established on the "wastelands", as these are often of large importance for fuelwood provision to the local communities [84].

Other land tenure conflicts are related with the rights to extract charcoal. As mentioned, charcoal production is often controlled by well-organized trade networks. In West- and in Southern Africa, conflicts were reported after charcoal merchants were granted harvesting licenses from local forest departments in forests considered as communal forests by local communities [10,87,88]. Even worse, insecure land tenure often leaves forest areas open for free and unregulated access by charcoal makers, impeding investments in sustainable charcoal production methods [18].

Table 3
The primary energy source of the rural, urban and overall households in Sub-Saharan Africa in 2000.

	Rural	Urban	Total
Firewood, dung, crop residues	94%	41%	75%
Charcoal	4%	34%	15%
Kerosene	2%	13%	6%
LPG	–	8%	3%
Electricity	–	4%	1%

Data from Bailis et al. [20].

4. Policy response

4.1. Moving up the energy ladder

4.1.1. The energy ladder

It is generally assumed that consumers shift to more efficient, more convenient and cleaner energy systems as their income rises [1,70]. As such, with increasing income, consumers move up the 'energy ladder', a concept postulated by Hosier and Dowd [89].

Dung is on the lowest rung of the energy ladder, followed by crop residues, fuelwood, charcoal, kerosene, LPG and, finally, electricity [70,71,89]. The energy ladder is illustrated in Table 3 by comparing the (poorer) rural and the (more wealthy) urban population of Sub-Saharan Africa [20]. Because a larger share of people will live in urban areas and because the average development will increase [33], energy use projections predict that the increase in fuelwood demand in developing countries will be lower than the population increase [3,10]

4.1.2. From firewood to charcoal

Charcoal is generally preferred over firewood by most households in developing countries. Charcoal is available throughout the year, is relatively clean and safe and can be stored easily and for long times, because it is not damaged by rain or moisture; in addition, charcoal can be purchased on the local market in small quantities and can be burned in cheap stoves [18,78]. Currently, a fuel switch from firewood to charcoal is taking place in developing countries, particularly in urban areas in SSA. This trend is expected to continue in the following years [4,10].

Scientists disagree over whether this shift is desirable or not. Some argue that this switch has positive effects for reducing indoor air pollution and that it should be stimulated [e.g. 20,55,90]. In SSA, a total shift from fuelwood to charcoal would be a cost effective measure reducing total child mortality in SSA by 6%, according to Bailis et al. [20]. Charcoal has the considerable advantage of being produced locally, without dependence on uncertain external factors, and of being part of the current system [20].

However, there are plenty of arguments why this fuel switch is not desirable. As previously discussed, the wood harvesting is often at the basis of land tenure conflicts and can cause forest degradation and biodiversity losses. In addition, the production of charcoal has very large GHG impacts and increases the risks of forest fires. Furthermore, though the combustion of charcoal produces less direct smoke than firewood, higher levels of indoor CO are formed.

Desirable or not, the large-scale switch to charcoal use is a reality that cannot be denied. It is very difficult to impose a policy against the will of the people; as such, it is very unlikely that

charcoal will disappear. Throughout the entire chain of production until combustion, there are possibilities to increase the sustainability of charcoal. This starts with a community-based forest management, in which sustainable harvesting can be guaranteed, continues with improved methods for charcoal production and ends with combustion of the product in improved stoves [78]. As such, improving the sustainability of the charcoal is probably the most effective measure possible for improving the sustainability of household cooking in developing countries and should be a key priority [14,18,48,53,56,57,78,88]. We will come back to a more sustainable harvesting, production and combustion in Sections 4.2 and 4.3.

4.1.3. From solid to liquid fuels

Kerosene and LPG (liquefied petrol gas) are the two types of fossil liquid fuels that are most commonly used for cooking in developing countries. Kerosene, a liquid fuel derived from oil, is often the modern fuel that is best available, as it can be easily transported and stored [12]. Although mostly burned in simple wick stoves, more advanced pressurized stoves exist that generate less smoke [55], although differences between stove burners were not confirmed by Smith et al. [68]. Risks of kerosene include poisoning for children in case of unsafe storage [55,70].

LPG is a by-product of the petroleum industry and is a variable mixture of mainly butane and propane, together with some other gases. It is stored in pressurized cylinders and is burned with gas stoves. It offers the great advantage that it can be burned almost completely and without polluting emissions [55], which is why some countries, such as China, prefer to skip kerosene and switch immediately to LPG. It is more difficult to transport, which reduces the availability in developing countries.

Advantages

Switching from solid fuels to kerosene and LPG offers several advantages, the most important one being the positive effect on public health [20,75]. Switching can also relieve women and children from the heavy burden of wood collection, is claimed to have beneficial GHG effects (but see Section 3.4) and to have environmental benefits in stopping deforestation, forest degradation and biodiversity loss (but see Section 3.2.1).

International policy

Switching to LPG or kerosene has become the top priority of the reigning international policy on traditional biomass use, as mentioned in Section 2.3. As part of the Millennium Goals, the UN Millennium Project [91] aimed to have 1.3–1.7 billion people switching from solid fuels to kerosene and LPG [12,16], in order to reduce the number of households using biomass as their primary cooking fuel by 50% by 2015. Hutton et al. [92] estimated the total benefits of meeting these goals at 91 billion $ per year. The largest benefit contributions came from time savings (44 billion $), mortality avoidance (39 billion $) and environmental benefits (6 billion $).

How can it be done?

Switching to kerosene and LPG involves a significant capital investments and high fuel costs for the households. Depending on the study, kerosene stoves cost between 6–10 $ [55] and 30–40 $ [12,91]. They have a lifetime of about three years [55]. The average capital investment costs (stove and canister) for switching to LPG are about 45–60 $ [12,55,91], and stoves have a lifetime of roughly 7 years.

The yearly costs for fuel are about 12 $ per person (counting at an average use of 22 kg $year^{-1}$ and an average fuel price of 0.55 $ kg^{-1} [12]) but vary greatly with location and in time. The prices of kerosene and LPG are linked with international market prices of fossil fuels, which are currently on the rise, and with inflation of the national currency compared with international currency.

Fuel subsidies can make the fuels more affordable, but are costly and economically inefficient, because the middle- and upper-class of the society benefit more from it than the poorest users [70]. Furthermore, kerosene and LPG are often used for other purposes than cooking, increasing the cost of the subsidiary system.

Financing the investment costs of LPG and kerosene stoves is seen by many as a more acceptable policy option than subsidizing fuel as such [70]. The required sum for purchasing all required stoves to meet the Millennium Goals mentioned above is 13.6 billion $, little compared to the benefits [92].

Experience in South-Korea and in Brazil points out that switching to LPG in developing countries is possible and can be very successful. The Brazilian government promoted the development of a LPG-delivery infrastructure in the entire country. Initially, LPG was subsidized (with 18%, on average) and a set retail price was installed. After 2001, however, LPG has no longer been subsidized, but the government has introduced a support program to help the poorest users to purchase LPG, halving the costs for the governments. The promotion of LPG is a big success: currently 98% of the households have access to LPG, 94% in rural households [93,94].

Drawbacks and pitfalls: energy ladder concept too simplistic and the case of the poorest people... Unfortunately, most fossil fuel switching programs have been much less successful than those in Brazil and South-Korea because of several reasons:

1. The dissemination of stoves does not guarantee their use. Stoves offered at limited or no cost are poorly valued by the households, and consequently resulted in very low use and maintenance [95–97]. Offering stoves through micro-financing is a valuable option, although this is not an affordable option for the poor subsistence users.
2. The stoves often do not comply with local traditions and cultures. Experience with improved fuelwood stoves learns that only stoves adapted to the local customs and preferences are successful in the long run [97,98].
3. Kerosene or LPG are too expensive for the poorer users, so unless a very efficient subsidy system exists, the poorest users are not able to participate in the switching [12]. Even in the highly successful program in Brazil, the poorest households switched back from LPG to fuelwood in the face of higher LPG prices [12].

In addition, even when programs are successful, complete conversion to kerosene or LPG does not take place [99], because the concept of the energy ladder-approach is too simplistic. Often, people use LPG-stoves only for lightning purposes [97]. It is observed in all continents that income increase results in complementing traditional energy sources with modern energy sources, rather than in replacing them [5,14,15,33,36,97,100]; as such, increasing income leads to increases in the number of energy sources, but does not replace them. In general, fuelwood even remains the primary fuel for cooking because people prefer to cook with the cheapest energy source [100–103].

Moreover, the approach is likely to lead to a collapse of the fuelwood market. The importance of fuelwood trade for local economies, particularly for the poorer part of the rural population, is totally ignored. In fact, if the market would indeed collapse, the poorest people might be worse of; they wouldn't have access to the new energy source and would lose an important source of revenues.

Expecting a large-scale switch to liquid fuel use is unrealistic

The Millennium Goals for switching to fossil fuels for cooking will most probably not be achieved [4]. This is hardly surprising given the fact that LPG or kerosene can only be introduced successfully if a stable and reliable supply is guaranteed. This includes (i) a well-accessible and secure access point, preferably a harbor, with refinery installations, (ii) a reliable transport infrastructure and (iii) the presence of an economy of scale that can cater LPG or kerosene efficiently. In addition, the experience in Brazil made clear that a switch can only be successful if (iv) the majority of the population

is wealthy enough to purchase LPG or kerosene without having to rely on subsidies and *v)* if the government is able to organize ánd to pay support programs to help the poorest users to purchase LPG.

It is needless to say that most developing countries are far away from meeting these requirements. As such, we agree with Mwampamba [48] and Zulu [14], among others, that proposing fuel switching as the solution in these countries is a misguided and disjointed energy policy, because it stands in the way of realistic and effective programs that focus on increasing the sustainability of solid fuel use.

4.1.4. From solid fuels to biogas

Biogas is a methane-rich fuel produced from the anaerobic digestion of organic material, such as animal waste, dung and crop residues [97,104,105]. The digestion requires sufficient amounts of water and relatively high temperatures; the optimal temperature is 36 °C [106], making biogas very suitable for (sub)tropical regions, though less for mountainous areas [104]. A biogas plant has two components, the digester and the gas holder [105]. Digesters for private use range from 1 to 20 m^3. The two basic types are floating drum and fixed dome digesters [107,108]. Fixed dome digesters are smaller and generally cost less. Recently, a third type, cylindrical digesters made of plastic, was introduced.

Advantages

Biogas is extremely clean burning; biogas stoves only emitted 10% of the GHGs emitted by LPG-stoves and were by far the cleanest stoves tested; the GWC of biomass stoves was 100 times less than that of firewood [68]. Biogas use furthermore has the significant advantage that it actually decreases GHG emissions, because the methane fraction that would otherwise escape to the atmosphere when the dung is broken down in the open air, is combusted and converted into CO_2 [55]. Moreover, the installations produce very good fertilizers as by-product [19,109].

Application

Family-size biogas installations have been enthusiastically promoted. The most success has been booked in China, where 17 million households used biogas in 2005, followed by India, with 3.8 million households and Nepal, with 170,000 digesters [110]. Since 2003, SNV, the Netherlands Development Organization, has actively promoted small-scale biogas installations in South and Southeast Asia, having reached 1.5 million people with 220,000 installations [111]. In Sub-Saharan Africa, however, the success of biogas has been very limited and the majority of installations is not functional [112–114]. As a consequence, the initial enthusiasm for biogas applications in Africa has somewhat dampened [12,55,70].

Constraining factors

Biogas programs have faced a number of problems. The most important constraining factors of biogas programs are the high capital investment cost as well as practical, technical and cultural problems [109,112,113].

Despite the attempts to reduce capital costs by using locally available materials (e.g. bricks, cement, clay, wood) and a relatively simple technology [104,112], installation costs are high. Smaller installations (4–6 m^3) in Africa cost between 500 and 875 US$ [105]; those in Asia tend to be cheaper (e.g. 180–340 US$ in Viet Nam) [112]. The material costs for the polyethylene tubular digesters are much lower, around 100 US$ [112], but this model is unpopular because of the much shorter lifespan [108]. Overall, biogas digesters cost much more than clean energy alternatives such as improved stoves or fossil fuel stoves. They can only be purchased with substantial support from governments and aid agencies; the number of installed plants falls dramatically after subsidies are cut back [112].

The most important practical problems are related with the input of dung and water. Per person, 0.34–0.42 m^3 of biogas is needed per day for cooking, which requires 8.5–10.5 kg of cattle dung [107]. As one cow normally produces between 10 and 20 kg of dung per day [107], the dung of at least two [115] to three [116] cows is needed to provide energy for cooking for one family. The combination of high installation costs and the high minimum amount of dung required makes biogas often only an option for the more wealthy families [55,108]. In addition, in most SSA countries, it is common practice to leave the cattle ranging freely, reducing the quantity of dung available for biogas production [108] and hence the capacity for biogas production.

Biogas production also requires large amounts of water: at least 180 liters (60 l fixed + 60 l per cow) are needed every day [112]. The access to cattle dung and to water in SSA resulted to be more of a problem than anticipated [70].

Similar to improved stove, electricity or fossil fuel programs, cultural and technical problems are also important constraining factors of biogas programs [12]. The design of the digesters is often not well adapted to the cultural preferences or to the given circumstances, particularly in projects in SSA [109,113]. In addition, biogas installations require a great deal of technical expertise in installation and in follow-up; this technical expertise is often not available or gets lost when programs are cut back [112]. In a study in Tanzania, only 20% of the owners of biogas installations used the gas for cooking and even then, biogas was complemented with firewood or charcoal [109]; all other owners either used biogas for lighting only and cooked with charcoal or firewood or did not use the installations because of technical problems, mainly problems of gas leakage (76% of the cases) and insufficient gas production (97% of the cases). In a study in India, only 35% of the installations in a certain state were still working after a number of years; 52% were not operating as a result of lack of interest and knowledge of the communities [117].

Policy implications

It is clear that several programs failed because of the "classic" problem in cooking energy-projects: a lack of understanding of the user's needs and the local situation. With an adapted digester design, a proper understanding of the local culture and an effective educational campaign, biogas programs can be more successful. In addition, biogas can also be produced from crop residues and other biomass, and these possibilities have not been fully harnessed, mostly as a consequence of limited technical knowledge [108,114]. On the other hand, the continued dependence on external financial support and the fact that only families of the upper and mid-income range have access to it are severe shortcomings.

Nevertheless, biogas has considerable potential where dung and biomass residues are abundant and where water availability is no issue, e.g. in large parts of India, East and Southeast Asia [12]. In these regions, biogas programs deserve support if a follow-up is guaranteed for several years and if the technical and cultural pitfalls are avoided. In Africa, however, the potential seems limited to those locations where dung/biomass and water are abundant [12] and is furthermore restricted because of the technical challenges and because villages are in general too dispersed to allow larger installations [12].

4.1.5. From solid fuels to electricity

Electric cooking is at the highest rung of the energy ladder. It is the cleanest and safest of all energy cooking alternatives and is commonly perceived as the most ideal solution for the traditional biomass cooking problem [e.g. 16].

Despite all this, the expansion of electric cooking in most developing countries has been very slow. The first reason for this is the limited availability of electricity [14,48,118]. Globally, more than 1.4 billion people have no access to electricity; 85% of them live in rural areas (Table 4). The access to electricity is particularly dramatic in Sub-Saharan Africa, where only 31% of the people, 28% if South Africa is not included, have access to electricity, compared

Table 4
Number of people without access to electricity by region in 2009 and 2030.[a]

	2009				2030			
	Urban	Rural	Total		Urban	Rural	Total	
	10^6	10^6	10^6	%	10^6	10^6	10^6	%
Sub-Saharan Africa	120	465	585	69	108	544	652	50
Latin America	4	27	31	7	2	8	10	2
Developing Asia	82	716	799	22	52	493	545	12
Developing countries	210	1229	1438	27	162	1045	1207	19
World	210	1232	1441	21	162	1052	1214	15

Based on data from OECD/IEA [119].

[a] 2030 projections are based on the New Policy Scenario of the World Energy Outlook 2010 [4], a scenario that takes all announced energy policy commitments into account.

to 79% at global level. In SSA (excluding South Africa), electricity consumption per capita is only 52 kWh per capita, about 2% of the world average; as such, the 791 million people of SSA consume roughly the same amount of electricity as the 19.5 million inhabitants of New York [119]. Current scenarios predict that by 2030 there will still be 1.2 billion people deprived of electricity in the world; the total number of people without access to electricity is even expected to increase in SSA (Table 4).

Although electricity availability is much higher in urban regions than in developing countries, electricity here is often erratic, with power fluctuations, frequent cuts and limited electricity capacity [118,120]. This unreliable availability urges people to have back-up energy sources and prevents them from investing in electric cooking appliances [57]. Furthermore, even if electricity is available, this does not guarantee that people actually have access to it, because high connection costs restrain people from getting electricity [57,103].

Nevertheless, as is shown in South Africa, with a strong governmental program, it is feasible to make electricity available to a very large part of the population in a time span of a few years or a decade [121]. In rural regions, this could be achieved most economically by local decentralized installations, often working on renewable energy such as solar power, wind energy or biofuels [118,122].

However, even if people have electricity in their homes, they use it for lighting, refrigeration or television, but often not for cooking. Madubanis and Shackleton [101] investigated how electrification affected energy use for cooking in five villages in South Africa. The results were astonishing: 10 years after the introduction of electricity to nearly all homes, the mean percentage of households using primarily wood for cooking had not decreased significantly and was still 94%; the percentage of households buying firewood as well as the average amount of firewood used per household had even increased. These findings parallel those of numerous previous studies, both in urban and rural areas, e.g. in South Africa [100], Mozambique [49], Zimbabwe [89,123], Kenya [124] and Tibet [125].

The most important reasons why people don't shift to electricity for cooking are the high costs of the cooking appliances and of the electricity tariffs [101,103,120]. Firewood or charcoal are used because they are free or the cheapest available energy source [101]. However, some studies indicate that this is relative: because electric cooking is much more efficient, biomass sources can be more expensive per unit of useful energy [57,103].

An efficient policy can significantly reduce electricity costs. Governments often subsidize electricity tariffs. Similar to fossil fuel subsidies, this policy is expensive and little efficient, as it favors the higher- and medium incomes: In Malawi, for instance, subsidies for electricity tariffs yearly cost the government 80 $ for a family of the lower income, 320$ for the medium income and 830 $ for a family of the upper-income [14]. A support program specifically set up for reducing the costs for connection, cooking appliance and electricity tariffs for the poorer households is probably much more effective, though more difficult to organize.

Still, even without cost factors, cultural aspects limit the success of electricity for cooking. As previously mentioned, the real energy ladder shows that increasing income or welfare leads to an increase of the number of energy alternatives rather than in a shift from one energy source to another; this principle also holds for electric cooking [100]. In a study in South Africa, for instance, it was observed that when electric appliances were present, electrical stoves were used mainly for re-heating of food, for boiling water or for short periods of cooking, whereas firewood and charcoal was used for preparing food that takes longer preparation times [126]. A study by Davis [100] in rural areas in South-Africa showed that electricity was only used for cooking by the highest income group.

As such, electricity, even provided at reduced costs, has limited potential as cooking fuel in developing countries [127]. This does not imply that electrification is not beneficial; electrification brings multiple benefits and can be seen as a vector for economic and social development [119,127]. However, it does imply that electrification should not be seen as the one solution for the traditional biomass issue [120], as is currently the case in several developing countries. This policy can even be counterproductive if it is used as an excuse for a stand-still. In Tanzania, for instance, electrification has been the key solution for tackling the traditional biomass problem since the country's independence in 1964; however, by 2005, less than 10% of the urban homes had electricity [48].

4.2. Efficient fuelwood conversion

4.2.1. Increasing the sustainability of charcoal production

Production process

Three distinct steps are involved in charcoal production. The first step, the drying of the wood, is endothermic and occurs at temperatures of 100 °C or below. The amount of energy required for this step is highly dependent on the moisture content of the wood (see Section 3.2.2); preferably, air-dried wood, with moisture contents of 12–18%, should be used [18,128].

The second step, the carbonization takes place once the wood is completely dry. First, the wood is heated to 280 °C in the pre-carbonization stage, producing small amounts of condensable (pyroligneous liquids, methanol and acetic acid) and non-condensable (CO, CO_2) gases. Once the wood reaches a temperature of 280 °C, pyrolysis or carbonization takes place; in this exothermic reaction the wood breaks down spontaneously into the carbonized residue (charcoal), condensable and non-condensable gases. Temperatures of ~400 °C are reached.

After this stage, the charcoal still consists for about 30% of tarry residue. This charcoal is brown, has a low HHV and produces a lot of corrosive smoke at combustion [128]. Heating the charcoal further to temperatures of 500–600 °C drives off and decomposes the tars. The final charcoal quality is highly dependent on the peak temperature reached [63,65,128]. Good charcoal contains at least 75% weight fraction of carbon, requiring a peak temperature of 500 °C; the remaining fraction consists of ash (mineral components,

Table 5
Overview of the most important charcoal production systems, with their conversion efficiencies and most important advantages and disadvantages.

Type	Conversion efficiency	Advantages	Disadvantages
Traditional methods			
Pit kiln	10–15%	No cost Local materials Flexible capacity and log size Mobility	Poor charcoal quality Difficult to control Contamination with soil Low conversion efficiency Re-absorption of pyroligneous acids Very slow Very high GHG emissions Sensitive to rainfall Large labor input
Earth-mound kiln	10–15%	No cost Flexible capacity Not fixed position Large logs can be used Mobility	Poor charcoal quality Difficult to control Contamination with soil Low conversion efficiency Slow Very high GHG emissions Sensitive to rainfall
Improved traditional methods			
Improved pit kiln	25%	Limited cost Better quality Flexible capacity Not fixed position Large logs can be used	Difficult to control Contamination with soil High GHG emissions Re-absorption of pyroligneous acids High GHG emissions Sensitive to rainfall
Casamance earth-mound	20%	Limited cost Better quality Less time Tar can be collected Flexible capacity Not fixed position Large logs can be used	Demands barrels for chimneys Contamination with soil Low conversion efficiency High GHG emissions Sensitive to rainfall
Brick and metal kilns			
Brick kiln	33%	Long life span (8–10 years) Can be built with locally available materials High conversion efficiency Good quality No contamination with soil All charcoal can be collected Easy operation Not sensitive to rainfall	Very expensive Skilled builder required Immobile Limitations in volume and log size Very slow (15 days) High GHG emissions
Metal kiln	25%	Mobile Less supervision required; easy operation Consistent conversion efficiencies Good quality No contamination with soil All charcoal can be collected Fast (2–3 days) Not sensitive to rainfall	Very expensive Short life span (2–3 years) Strong limitations in volume and log size Not transportable in hilly terrain High GHG emissions
Retort methods			
Adam retort (ICPS)	35%	High efficiency Easy to operate Good quality Locally available materials Long lifespan Low GHG emissions Very fast (2 days for full cycle) No contamination with soil All charcoal can be collected	Limited experience Rather expensive Immobile Limitations in volume and log size Highly skilled builders required

Based on [18,64,128].

present in the bark) and tar. High-quality industrial charcoal has a carbon content of 80% or higher [128].

In the third and final step, the charcoal cools; it is important that this occurs in oxygen-free conditions to prevent combustion. After this, the mound or pit is opened and the charcoal is collected.

Usually, the efficiency of charcoal production is expressed by its conversion efficiency, the amount of charcoal produced per kg of dry wood. However, this does not reflect the carbon content of the charcoal product; note that the conversion efficiency decreases when peak temperature increases, because the tar fraction is lost, but that the quality of the product improves [66]. Better expressions of the production efficiency are the ratio of the lower heating value of charcoal and the lower heating value of the wood (usually at 15% moisture content) or the ratio of the amount of carbon in the charcoal and that of the wood; however, conversion efficiencies will further be used to characterize the kiln types, because other efficiency data are not available for most kiln types.

Kiln types

In developing countries, charcoal is predominantly produced in traditional pit or earth-mound kilns. In pit kilns, the wood is placed in specially dug holes in the ground; in earth-mound methods, the wood is first stacked in piles. Soil is used to cover the wood and create oxygen-free conditions. Both systems result in very low efficiencies and very high greenhouse gas emissions, because:

1. The heat of the process is provided by the combustion of a fraction of the wood. The bad isolation further increases this fraction.
2. The air circulation is limited. Consequently, the cooling and heating is irregular; some areas are burnt to ashes whereas the temperature in other areas will never reach 500 °C, resulting in charcoal of bad quality.
3. The operation requires highly skilled workers and constant vigilance. For the combustion of a fraction of the wood, a limited amount of oxygen needs to enter the system through holes. When the carbonization begins, the color of the smoke changes from white to yellowish, and part of the air holes need to be closed. After a few days of burning, the volume of the wood will decrease, leading to openings in the mound or the pit cover; these must be covered in order to prevent combustion.
4. The tar fraction is not recovered and almost all gases are emitted to the atmosphere, including the producer gases with high CO and CH_4-content. The soil absorbs a part of the pyroligneous acid fraction. However, during rainfall, this fraction is leached again to the lower-lying charcoal, where it is re-absorbed. Particularly in pit kilns, this leads to charcoal of bad quality.

Additional disadvantages of these traditional systems are the sensitivity of the kilns to rainfall, the contamination with the soil and the slow rate of the process.

However, there are good reasons why these traditional methods are still predominantly used in developing countries (Table 5). Most importantly, they can be constructed without any material cost, with very little equipment and at virtually any location. In addition, the pits or mounds can be constructed for any volume of wood and for any size of logs; as such, these systems are extremely flexible and match well with the dispersed nature of charcoal production [53].

Several improved kiln types have been developed. The advantages and disadvantages are given in Table 5; Overviews and detailed descriptions are provided by FAO [128] or Foley [129]. These kilns can be roughly divided into three types: improvements of the traditional pit and earth-mound kilns, brick or metal kilns and retorts.

The production process of the improved traditional, brick and metal kilns is very similar to that of the traditional kilns: the heat is provided by the combustion of a fraction of the wood and the producer gas is not used as an extra energy source but is emitted into the atmosphere; in the improved Casamance earth mound, the tar fraction can be partly recovered.

The improvement of these systems lies in the increased conversion efficiency through (i) a better air circulation, using metal pipes, (ii) a better stacking of the wood and more efficient air inlets and (iii) through a better isolation, by using bricks or metal plates. In general, the higher efficiency of these systems comes at the price of higher material and equipment cost and of reduced flexibility, in terms of total volume, log size and mobility. Unfortunately, the greenhouse gas emissions of these systems remain high to very high.

The Adam-retort or Improved Charcoal Production System (ICPS) is a relatively new system for which technology of large-scale industrial charcoal factories was downscaled to systems of 7 m^3. It is described in more detail by Adam [65]. Retort technology means that the charcoal is produced in a closed container and that the smoke and gases leave the system through one opening. The heat energy for the drying and pre-carbonization phase is provided by combustion of low-quality biomass (e.g. branches, crop residues...) in a separate chamber. During the carbonization stage and afterwards, the energy is (partially) provided by burning the producer gases. This way, high conversion efficiencies are combined with strongly reduced greenhouse gas emissions, as 75% of the methane fraction is combusted [65]. The retort can be built with locally available materials and costs between 300 and 500 US$. Every 2 days, 250 kg of charcoal can be produced from 700–800 kg of wet biomass.

How can improved charcoal production systems become implied?

Despite the tremendous potential environmental benefits, improved kiln programs have received remarkably little attention from international institutions, non-governmental organizations or from the scientific community. There are several reasons for this.

First, in the past, improved kiln programs have been very little successful and the systems have rarely been adopted permanently [129–131]. Even the penetration of the Casamance kiln, generally regarded as one of the more successful improved systems [131], is very limited, despite the large similarities with the existing traditional earth-mound system and the limited capital investments required [18,130].

Second, field measurements show that conversion efficiencies of the improved kilns in reality overlap with those of the traditional pit and earth mound kilns [53,64]. There is a large range in conversion efficiencies, indicating that other factors, mainly the skillfulness of the charcoal producers and the wood moisture content, are at least as important as the type of kiln [64]. These measurements did not include the recently developed Adam retort system.

The third and probably most important reason for the limited interest in improved charcoal kilns is the reigning negative view on charcoal production, which is translated in bans in several developing countries. This is illustrated by the energy policies of Kenya and Ethiopia: although these countries favor improved charcoal stove programs, charcoal production itself is illegal [18]. This is likely also the reason for the failure of a large part of the improved kiln programs so far; if the production is illegal, the kiln method must be mobile and should not require any large equipment; in addition, the illegal nature holds down investments in the kiln methods, makes it impossible to communicate with and monitor the activities of charcoal producers and prevents local communities from producing charcoal within the framework of sustainable forest management. This, in addition with the insecure land tenure, also implies that the costs of sustainable forest management cannot be covered in the production price. As a consequence, charcoal prices only reflect harvesting, production and transport, which further holds back investments in sustainable forest management and in improved charcoal kiln methods [14,18,48,56].

As such, it is clear that improved kilns programs can only be successful if the forest policy is adapted and if they are embedded in much larger programs that also include initiatives to stimulate community-based forest management, efficient local and national forest administration and that involve the charcoal producing sector.

From the previous section, it is clear that from a technical perspective the most promising type of charcoal production system is the Adam-retort systems. However, relatively little experience exist with these systems, which are furthermore relatively expensive and depend on skilled workers for their installation. They have limited or no mobility and are only suitable for situations where charcoal can be produced. by local communities. In other cases, kiln types best fitted for the local cultural/social (e.g. produced by local communities or not; skilled workers available for production and maintenance or not, financing possibilities...) and environmental (e.g. climate; wood types; only wood or also other biomass sources?) conditions should be selected.

4.2.2. Improved stoves

Four decades of experience

Improved stoves can reduce indoor air pollution and greenhouse gas emissions, save a considerable amount of fuelwood biomass and partially relieve women and children from the burden of wood collection. Because of these combined benefits, improved stove

programs were already incorporated in the first fuelwood crisis development programs [8]. However, as most initial development programs, a large number of these projects failed [132]. The reason for this was most often that the user's needs and wishes were not taken into account. For instance, it was generally assumed that people were willing to pay for improved stoves because reductions in fuel collection or expenditure to fuels and health benefits through smoke reduction were priorities for biomass-using people [36]. However, it became clear that health problems associated with indoor air pollution were not well known and that most people gave priority to more immediate and visible problems such as water supply and sanitation [8,132,133]. Hence, in regions with high biomass availability, interest in improved stoves was limited. People who actually had to pay for their fuelwood were more willing to invest in improved stoves in order to save money [134].

In addition, errors were made in the design of the improved stoves. Particularly in the first years of the fuelwood development programs, improved stoves were designed to concentrate on increasing thermal efficiency, because fuelwood shortage was thought to be the most crucial problem [135]. Fuel use efficiency is mainly obtained by increasing the heat transfer efficiency, whereas lower emissions are obtained by increasing the combustion efficiency [69]. Therefore, stoves with high thermal efficiency do not necessarily have lower emissions. In fact, tests by Smith et al. [68] proved that improved stoves had higher fuel efficiency but emitted more PICs than traditional stoves.

Over the years, however, lessons were learnt from the initial mistakes. Recent designs of improved stoves provided both lower emissions and higher thermal efficiency than traditional stoves [19,62]. In 2007, 220 million improved stoves were in use around the world [19]. By far the largest part, 175 million, were in use in China, provided through the very successful *Chinese National Improved Stoves Program*. In a society where 80% of the households co(partially) rely on biomass for cooking [20], 95% of these households disposed of an improved stove in 2007 [19].

In India, the National Program on Improved Chulhas was less successful: after 17 years, in 2000, 30 million stoves were dispersed, but less than a third was still in use [70] and only 10% of the households disposed of an improved stove [8]. One of the differences between the Chinese and the Indian programs was the organizational approach. In the Chinese program, direct contacts between the central governments and the county were established, bypassing the bureaucracy at intermediate levels, and efforts were concentrated in a few pilot counties in the first part of the program [70,96]. In contrast, the Indian program was launched nation-wide, resulting in dispersed efforts and diluted financial resources. In addition, the administration involved several levels [70,95].

In Africa, an estimated 8 million improved stoves were in use in 2007 [19]. Although most projects were successful, they were limited in size and scale. In most rural areas, improved stove use is still very limited [19]. Kenya has had the most successful program, with 3 million improved stoves now in use. Ethiopia has similar numbers, and 1.3 million stoves are in use in South Africa [19]. Uganda, finally, has ambitious plans to increase the number of increased stoves to 4 million by 2017.

Recommendations for successful programs

The experience with improved stove programs allows formulating general recommendations for local or national improved stove projects.

a) Stove design*:* Understanding the user's needs

It is absolutely crucial that the improved stoves are designed according to the user's needs [36]. This implies that several aspects are taken into account in the design of the improved stoves, most importantly [36,68,97,136]:

1. *Cleanliness:* If possible, stoves should have chimneys, burn with little smoke and should be easy to clean.
2. *Time saving:* Easy lighting and maintaining alight and fast cooking are generally considered priorities.
3. *Fuel flexibility and compatibility:* Often, users want to shift between firewood, charcoal and dung.
4. *Cooking:* The heat output should be controllable and the stoves must be compatible with local food preparation demands.
5. *Safety:* Stoves should be safe and should cool quickly after use to prevent burning wounds.
6. *Comfort:* Stoves should be easy and comfortable to use, should be portable and must not occupy too much space.
7. *Cost and durability:* A good match between low cost and high durability should be aimed for.
8. *Attraction and familiarity:* Social aspects are often ignored but play a vital role in determining the success of the stoves. Stoves should be attractive and are in some regions preferred to be not too different from the traditional stoves. In assessing the most desirable design, gender aspects should not be ignored. Although the manufacturing and purchase of the stoves is mostly done by men, the stoves' success finally will depend on the women. They should be actively involved in the design and monitoring programs [97].

It is furthermore clear the most important goal of improved stoves is the reduction of indoor air pollution and related health impacts. However, this should go hand in hand with a decrease in GHG levels [68,69]. All in all, the stove design is a crucial but time-consuming and expensive phase of the program. In the large majority of the successful programs, this development phase relied on donor or state funding [10,137].

b) *A sustainable project: Finding a balance between commercialization and funding*

i) Commercialize the improved cooking stoves

The large majority of the successful programs combined donor or state funding with commercialization by local businesses [137]. In most developing countries, starting up a business of this size is a huge challenge. As such, institutional and financial opportunities should be provided [137]. Stoves can best be sold as commercial products, rather than be given away freely: as mentioned, free stoves are poorly valued by the households and are consequently not used or not properly maintained [95–97]. Commercialization offers several other advantages [97,135]:

- Local knowledge is generated on the assembly and reparation of stoves, stimulating the local economy.
- This approach is cost-effective and provides the best guarantees that the designs will be adapted to the local requirements.
- Manufacturers will only be able to market their products commercially if they are durable and of good quality.
- In order to be able to sell their products, the local manufacturers must advertise them and inform the people of the advantages associated with improved stoves, through campaigns in local media or field trials in local villages. This increases the people's knowledge on and awareness of the associated problems as well as their willingness to pay and to maintain the stoves in good state.

Commercialization offers the best guarantee that the improved stoves will still be available after the funding for the project stops and that people will be able to replace their stoves when they are worn-out after a couple of years. The support from the donor or state funding should be in the form of education, training, technical assistance and commercial guidance

to the designers and manufacturers as well as in the form of information campaigns for the local people [97,137].

ii) Provide a system of microcredits for subsistence users

Although prices of improved stoves are often very low [12], commercialization of improved cooking stoves has problems reaching the poorest [137]. Poor households have often problems paying the entire sum in one transfer [10,138]. Still, there is evidence that if even poor subsistence users are willing to (help) pay for durable improved stoves [139]. This could be enabled by providing microcredits to these users.

iii) Quality control

The quality of the stoves should be independently monitored and the results used to improve the stove design and fabrication.

Conclusion: a cost-effective and realistic measure, although success is not guaranteed

Clearly, a lot of factors determine the success of improved stove programs. Nevertheless, improved stoves offer a wide number of benefits. For instance, the use of improved stoves can reduce air pollution by more than 50% and can save 10–50% of biomass consumption for the same cooking service [12,19].

Moreover, if the stove design takes cultural aspects into concern, improved stoves are, unlike other alternatives, widely accepted [55] and can therefore become established in the local cultures. The costs for improved stoves vary widely with the design and the country [55], ranging from 2 to 3 $ in Ethiopia to 15 $ in Guatemala [12] and 30$ in Mexico [137]. Still, these costs are substantially lower than those for kerosene or LPG stoves [12,55,91]. It was estimated that providing improved stoves to 50% of the families currently relying on traditional biomass for cooking would cost 23 billion $, whereas it would generate 173.3 billion $ in benefits; 50% of these benefits would come from time saved in cooking and fuel collection, 21% from fuel savings and 19% from health benefits [92]. This makes improved stoves the most cost-effective household energy intervention; more effective, for instance, than switching to kerosene or LPG [92]. We therefore conclude that improved stove programs should remain a policy intervention of very high priority.

4.2.3. Ventilation

The indoor exposure to pollutants can be significantly reduced by using proper ventilation systems [55]. Hoods and chimneys are the two most common types of ventilation. Hoods have the advantage of providing constant ventilation for smoke to escape [97]. Studies demonstrated that hoods are much more effective in extracting smoke than ventilation through windows [97].

Chimneys are even more effective, because they largely prevent the smoke from entering the room. They are most effective when they reach more than half a meter above the roof line [96]. A disadvantage of chimneys is that they reduce the fuel efficiency, by creating an added airflow; this also reduces the attractiveness to the users [139]. They also tend to be more expensive than hoods. The cost of chimneys is roughly equal to that of improved stoves [55].

A recent study by Rehfuess et al. [75] on ALRI mortality in children in Sub-Saharan Africa was the first to quantify the effect of ventilation in terms of health impact. Children of households cooking with solid fuels without chimneys or hoods had 268% more chance of dying of ALRI than children of households which used clean fuels (electricity, LPG and Kerosene). However, children of households cooking with solid fuels with chimney or hood did not suffer from more ALRI mortality than children from households with clean fuel use. These results confirm the findings by Dasgupta et al. [140] that particulate levels in houses cooking on firewood but with good ventilation were comparable with those in houses using LPG.

As a consequence, the effectiveness, simplicity and low costs of ventilation systems make hoods and chimneys, in combination with improved cooking stoves, the most cost-effective way to reduce indoor air pollution and the related health problems [12,75,141]. These health benefits outweigh the disadvantage of higher emissions of GHG, as measured by Smith et al. [68].

4.3. Fuelwood provision

4.3.1. Banning fuelwood extraction works counterproductive

In several developing countries, particularly in Sub-Saharan Africa, governments responded to the fuelwood gap threat by banning fuelwood logging in the largest part of the (state) forests [14,48,56]. Although the fuelwood crisis-narrative was rejected long ago, the narrative is still present in the heads of many governments. Consequently, the forest policy has not changed, despite the fact that it is not effective in stopping deforestation, as this has other causes.

In places where bans are followed up, the pressure increases on the remaining lands where wood can be extracted, with the risk of over-exploitation and land degradation. However, as people have no other choice than to gather fuelwood for their energy provision, the bans on fuelwood logging are in practice often not followed up. In this situation, the ban on fuelwood extraction or charcoal production works counterproductive: it criminalizes the largest forest sector and with it the people employed in it, making it impossible to control or to improve the procedures and techniques applied [14,18,48,56], as discussed in Section 4.2.1. Furthermore, the ban denies the government of a large sum of potential tax revenues. In reality, however, charcoal production is often taxed illegally [18]: In Malawi, an estimated 12 to 20% of the charcoal retail values goes to bribes [14]. As such, the charcoal ban promotes corruption and creates related local problems.

4.3.2. Government-controlled woodlot plantations

As mentioned in Section 2.1, the emphasis of the fuelwood crisis programs was on fuelwood provision. Often encouraged by international institutions as the World Bank [14], governments invested massively in the establishment of woodlots [8]. Some of these programs are still running nowadays. The wood from these woodlots is sold for low prices at local markets. The rationale behind this policy is clear: Offering people very cheap firewood ensures energy provision, avoids unsustainable harvesting in the remaining natural forests, delivers cheap energy to the poorest and relieves women and children from the heavy burden of wood collection.

In reality, however, results are not very positive. Woodlot plantations were often not well adapted to the local situation and failures emanated from the use of inappropriate tree species or the selection of inappropriate sites [11]. Even when woodlot plantations were productive, the costs for land, labor and transport were not compensated for by the revenues from fuelwood sales and the plantations were unprofitable [142].

Moreover, woodlots were often planted on communal lands, which previously supplied fuelwood and other products to subsistence users, who lost access to these sites after planting. In addition, this approach ignores the complexity of the fuelwood provision markets and the economic importance of fuelwood trade. As such, although cheap fuelwood might benefit the urban poor, it actually aggravates the situation for the rural poor, which can trigger further movement of people to cities, with all due consequences [8,10,14]. In addition, local fuelwood shortages are not detected through rising prices, because subsidized fuelwood prices keep fuelwood prices low [10]. The low prices restrict investments of farmers in increasing the fuelwood supply from their lands and hence prevent the markets from being corrected automatically. From the above evaluation, it becomes clear that the establishment

of fuelwood energy plantations is not a sustainable or profitable solution for increasing the local wood supply [143].

4.3.3. Community-based forest management

Actively involving the communities in the management of the local forests provides an alternative for banning people from the natural forests or for increasing wood supply in state-controlled woodlot plantations. This implies a transfer of power to the local communities, entrenched in a legal system, and a support and control system protecting these legal rights [8]. Crucial in this approach is the recognition of the importance of forests and woodlands for the rural livelihoods and of the local communities for providing sustainable forest management [88].

Community-based forest management (CBFM) has not always proven successful. One important concern is that fuelwood prices are often too low to compensate for the costs related to CBFM; in these cases, the low market value for fuelwood urged the farmers to use the wood for other ends [11,144]. However, even in these situations, the availability of fuelwood for the local community improved, decreasing the burden of collection [10,145].

Other major problems are related to the organization of the forest committees. Some forest committees turned out to be corrupt elite clubs monopolizing the benefits and taking management decisions in their own interest rather than in that of the communities [14,146]. The success of CBFM proved to be closely related to financial accountability and sound record keeping; hence, to a non-corrupt and reliable control mechanism, from inside and outside the communities.

In addition, CBFM often suffered from the ban on fuelwood logging, as this stood in the way of legal income generation [14]. Moreover, participatory forest management also requires efficient conflict management, as conflicts within the communities and with outsiders are common. Special attention in needed for those forests that are important for charcoal production, controlled by external commercial entities [8].

A third problem is the fact that CBFM should be supported by a reliable government forest department. Transparency of the government and participatory approaches within an organized legal framework offer the best guarantees for a sustainable use of these forest sources. Unfortunately, governments are often very suspicious about participation of the local communities, a remainder of the fuelwood crisis-narrative. Moreover, inefficient government and forest department structures, together with problems of local corruption, hinder CBFM.

Nevertheless, these problems are caused by flaws in the process rather than in the concept of CBFM and are therefore correctable [14]. CBFM has proven successful in reducing communal tensions and in gaining sustainable fuelwood benefits [147], for example in Sub-Saharan Africa [see 87 for an overview] and in India, in the framework of the Joint Forest Management Program [148]. It offers the considerable benefit that the fuelwood economy becomes legalized, opening the door for control, development and training [78]. As such, it is commonly accepted that CBFM forms one of the key pillars of sustainable fuelwood production [e.g. 8,10,14,88,145,147].

4.3.4. Integration of fuelwood in agroforestry systems enhances local firewood supply

The large importance of non-forest trees in supplying fuelwood demonstrates that fuelwood supply is one of the multiple functions trees fulfill in agroforestry systems. Fuelwood is often only a by-product of agroforestry, because the low fuelwood prices make it normally unprofitable to reserve land with the specific aim of fuelwood production.

However, in regions where local fuelwood supply is limited or where collection distances are long, farmers consider fuelwood provision as one of the most important functions of agroforestry trees [143,149] and plant trees mainly for fuelwood provision [e.g. 150,151,152]. In these areas, it can make sense to adapt the agroforestry system to increase fuelwood production. The two most important agroforestry techniques for producing fuelwood are rotational woodlots and improved or tree fallow system [153].

Rotational woodlot systems

In rotational woodlots, trees and crops are grown in three phases [142]. In a first phase, crops and trees are planted and the crops give yield until crown cover becomes too dense. In the second phase, crop cultivation is abandoned and the area is used as grazing land for cattle, until the trees are harvestable. In the third phase, trees are harvested, and crops are planted in between the tree stumps. Coppice shoots are pruned to single stems, in order to concentrate the growth whilst allowing crop production [142].

Mainly fast-growing species, such as local or Australian *Acacia* species, are used [142,153]. Important by-products are fodder, gained from leaves, pods and seed, and fertilization through nitrogen fixation. In Tanzania, where indigenous *Acacia* species are used, coppice rotation length is 7 years, and the woodlot areas are divided into 7 strata [142]. Australian *Acacia* species generally grow more rapidly, with reported coppice rotation length as short as two years [153]. However, the high water use and drought sensitivity of these species cause concern [153].

Rotational woodlot systems can be very productive. Yields of up to 100 tons ha^{-1} of fuelwood biomass have been reported [154], and trials in Tanzania showed that rotational woodlots are the most economically profitable technology for fuelwood production [142]. The most important constraints for a wider adoption of rotational woodlots are the limited access to land by farmers [155], the lack of training of the farmers, inadequate seed supply and the narrow range of the species used [153].

Tree fallow or improved fallow systems

In tree fallows or improved fallows, nitrogen-fixing tree species are planted during the fallow period, aiming at a rapid increase in soil fertility and later crop yields [156,157]. Tree species provide more efficient soil recovery than traditional fallow systems thanks to the higher rate of N-fixation and carbon storage in the soils [156]. Moreover, trees are more efficient in weed suppression than herbaceous species, particularly in suppression of *Striga*, a parasite on maize and other cereal crops [153,156,157].

The productivity depends mainly on planting density, site conditions and species used [157]. Planting density is generally very high (more than 100,000 plants ha^{-1}), in order to maximize nitrogen fixation. Several species have been successfully used in tree fallow systems, specifically good results were obtained with *Sesbania sesban* [153]. The high planting densities require establishment through direct seeding or vegetative cuttings, as seedling planting is too expensive, unless the farmers raise the seedling in their own small-scale nursery [153]. Fuelwood production in tree fallow systems can be very high. Areas are usually left fallow for 1–3 years [156,157]. Biomass production of up to 27 tons ha^{-1} has been reported [158]; Jama et al. [157] reported production between 5 and 11 tons ha^{-1} after 1 year for tree fallow systems in western Kenya. Main challenges to the widespread uptake of the technology include land constraints, property rights, limited availability of seeds and the knowledge-intensive nature of the technology [155].

5. Conclusions

5.1. Adapting the policy of national and regional governments

It is clear that the reigning national and regional policies in several developing countries are counterproductive and that their adaptation is badly needed to enable a more sustainable use of solid wood fuels.

First of all, governments should be convinced to renounce the fuelwood crisis-doctrine. As a consequence, governments should stop supporting peri-urban fuelwood plantations that supply the urban markets with underpriced fuelwood, because this policy is very expensive, inefficient (it does not halt deforestation, which has other causes than fuelwood extraction) and denies the rural population from an important source of income.

Moreover, several countries have banned fuelwood logging and charcoal production in (state) forests, as well as charcoal trade in general. As discussed, this policy has several adverse consequences; most importantly, by denying the reality of an increased charcoal demand, it blocks a sustainable charcoal production and industry and triggers local corruption. Legalization of charcoal enables a better control and regulation of the production and trade of charcoal, opens the markets for local communities and offers the best guarantees for a sustainable wood use and for fair market price [53]. As discussed, governments should promote community-based forest management. This, however, requires strong and reliable (i.e. non-corrupt) regional and local forestry administrations.

In addition, governments should provide clear and secure land tenure rights to the local communities; this is not only an absolute prerequisite for community-based forest management, but can also prevent conflicts with external charcoal producers.

Several governments in developing countries, particularly in SSA, consider a transition to electricity or fossil fuels use as the solution for the energy problem. However, the requirements and conditions needed to realize this within a reasonable time span are rarely achieved. As such, where its realization is very unlikely, governments should stop using this energy transition as an excuse for a stand-still on energy policies; it creates a lack of interest and investments to increase the sustainability of traditional biomass use.

5.2. Rural areas

In most rural areas, firewood is likely to remain the most important fuel for cooking. Here, the policy focus should be on the avoidance of health damage due to inside air pollution. Kerosene and LPG will not be an option in most regions, unless the strict conditions, discussed in Section 4.1.3, are fulfilled. Similarly, although electrification brings multiple benefits, its availability will not have a large impact on household cooking. As such, the major policy focus in rural areas should be on promoting improved stoves and chimneys, the combination of which results in indoor air pollution levels comparable to those of fossil fuel stoves. The recommendations for successful improved stove programs, formulated in Section 4.2.2, should be followed as much as possible.

In addition, in regions where local fuelwood shortages exist or where the task of firewood collection sheds a heavy burden on the households, initiatives should be promoted to increase the local firewood availability. This could be achieved by two distinct options.

First, fuelwood availability can be increased by allowing people to collect wood in the existing forests, within the framework of community-based management of the local forests. Experience learns that community-based forest management is only successful if a reliable body supplies information and support and controls the finances and record keeping of the management. Ideally, this controlling body is the local forestry administration; as such, the stimulation of community-based forest management should go hand in hand with the establishment of a reliable local forest administration and the adaptation of the national and local forest legislation, e.g. on land tenure issues and on fuelwood production and trade, as explained above.

Second, the local firewood availability could be enhanced by promoting agroforestry systems such as improved fallow systems and, in case of severe shortage and low to medium land pressure, rotational woodlot systems. Local development programs must focus on providing information and support to the farmers as well as establishing and supporting local tree nurseries, in order to provide the farmers with adequate planting material.

In tropical regions where cattle dung/biomass and water are not limiting, biogas provides an interesting alternative fuel for cooking. However, it should be clear that biogas should always be only one of several cornerstones of development program aiming to increase the sustainability of cooking, because biogas technology depends heavily on specialist external expertise and on external funding and tends to favor medium- and high-income households. In addition, biogas programs often faced technical problems, including problems of technology transfer and capacity building, as well as cultural problems, leading to very low dissemination [5].

5.3. Urban areas

In urban areas, electricity and fossil fuels is available to a higher percentage of households than in rural areas, and transitions towards these less polluting energy sources are easier to achieve. Still, although these transitions deserve policy support, they should always be complemented with initiatives to increase the sustainability of traditional biomass use; the undeniable reality is that the largest shift in fuel use in urban areas is a shift towards charcoal. As such, the policy should focus on stimulating a sustainable charcoal production system and on improving charcoal (and firewood) combustion.

Improving charcoal and firewood combustion can be achieved with the same initiatives as in rural areas, namely by introducing improved stoves and chimneys. Charcoal production holds the risk of unsustainable wood harvesting and of very inefficient conversion to charcoal. As discussed in Section 4.2.1, increasing the sustainability of charcoal production therefore requires a combination of initiatives to introduce improved kilns, preferably the Adam-retorts for fixed and the Casamance earth-mound kilns for mobile applications, and initiatives to provide opportunities for sustainable forest management, including adjustment of the national and regional policies, as was discussed in the two sections above.

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